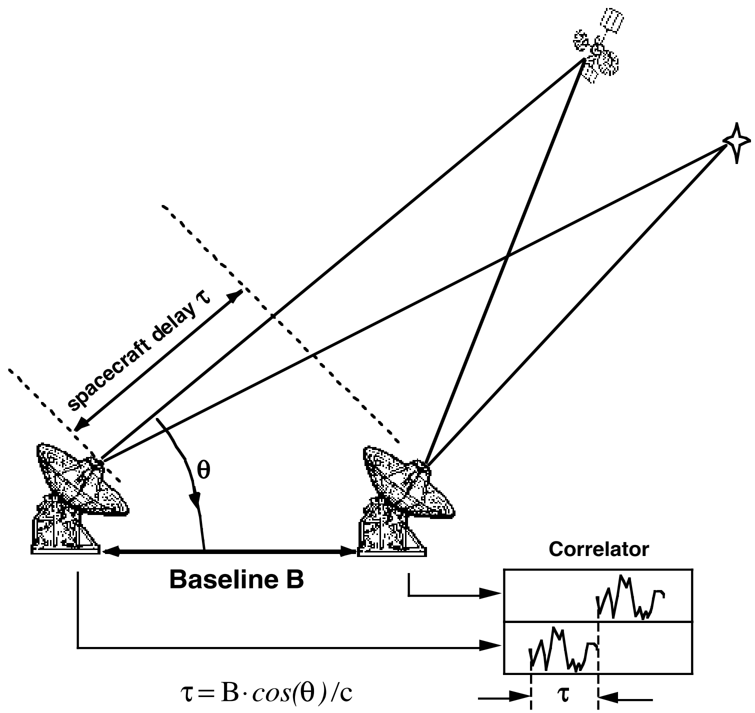
ΔDOR Technology Improvements

Chris Volk & James Border

Jet Propulsion Laboratory
California Institute of Technology

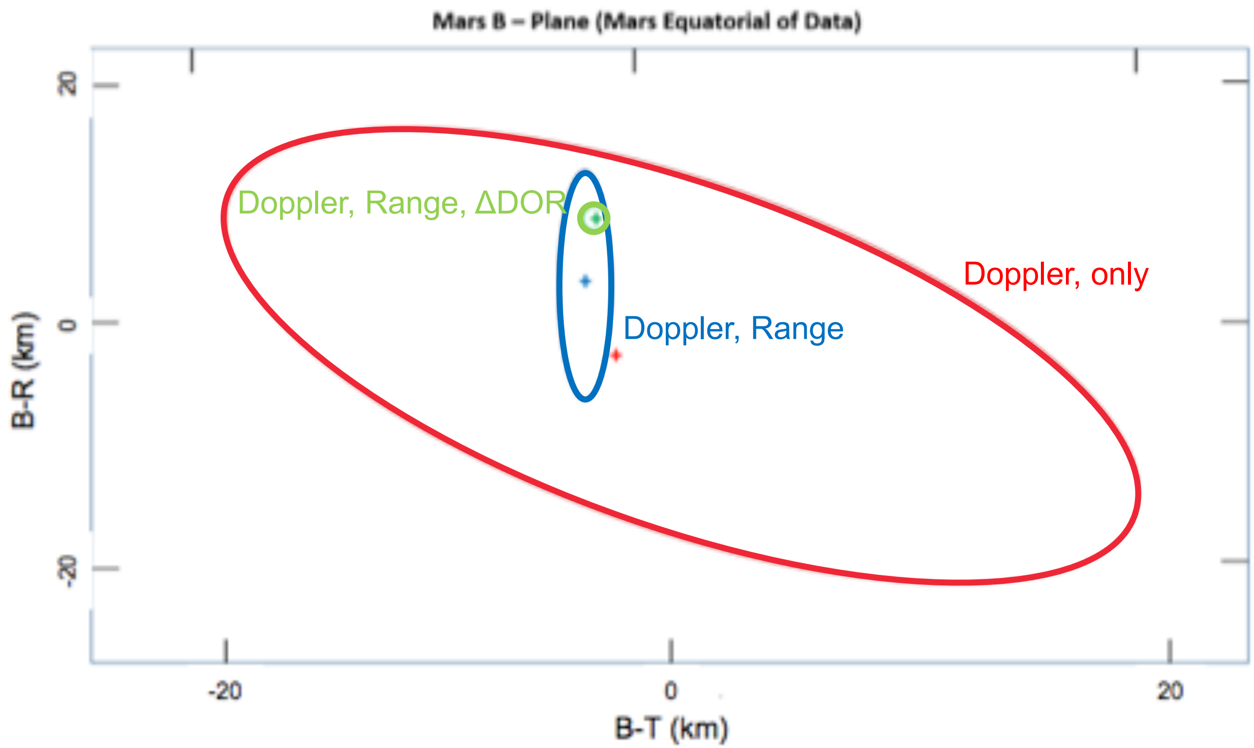
Delta Differential One-Way Ranging (ΔDOR)

- ΔDOR uses interferometry to measure spacecraft angular position in the radio reference frame
- Observations from 2 (long) baselines are needed to measure both components of angular position

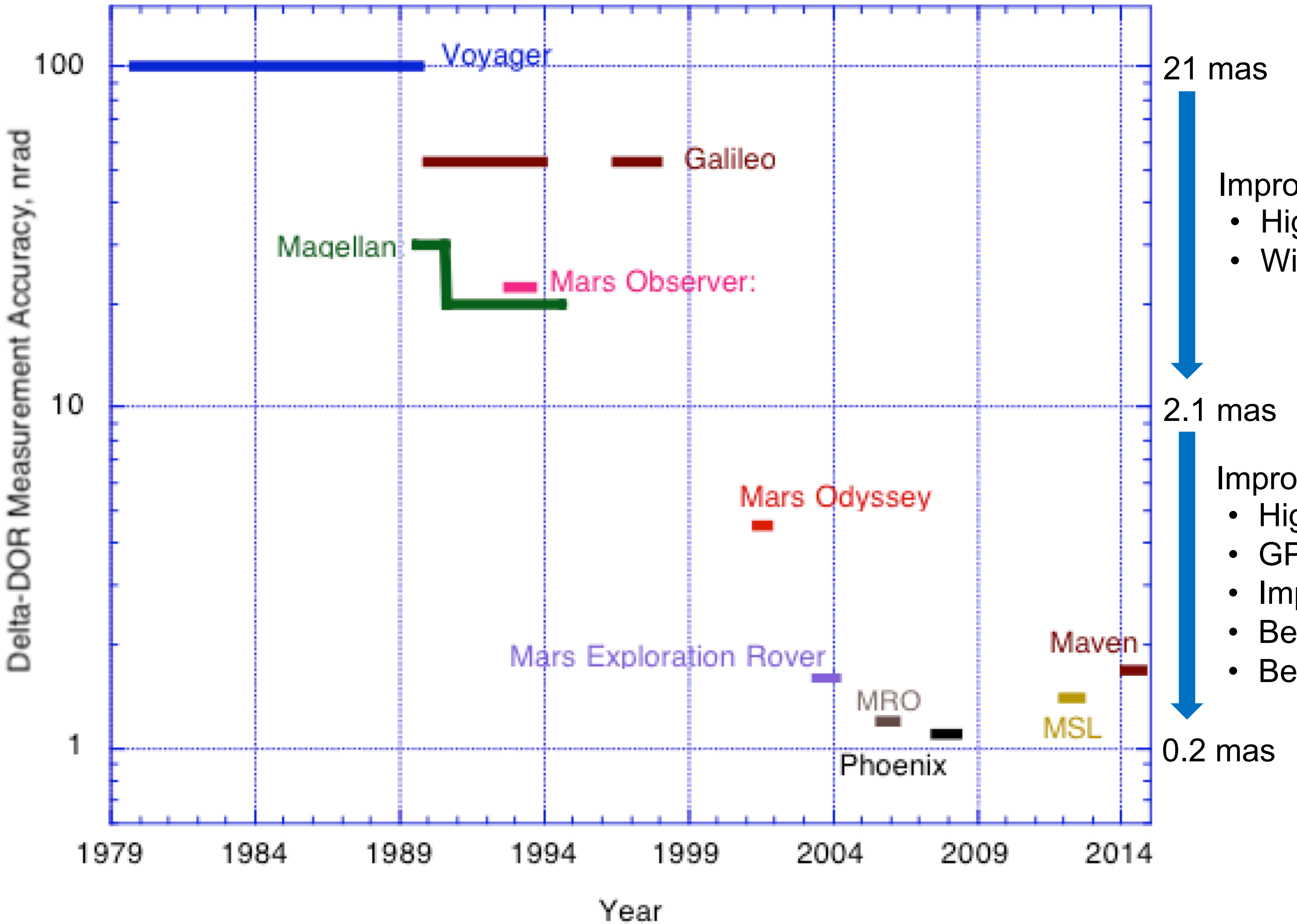


ΔDOR Navigational Purpose

- Complements line-of-sight Doppler and range to provide plane-of-sky coordinate targeting for critical events
  - High accuracy is needed for targeting a Mars landing
  - 300 m plane-of-sky position accuracy at Mars (~1 AU)



ΔDOR Historical Accuracy Improvement



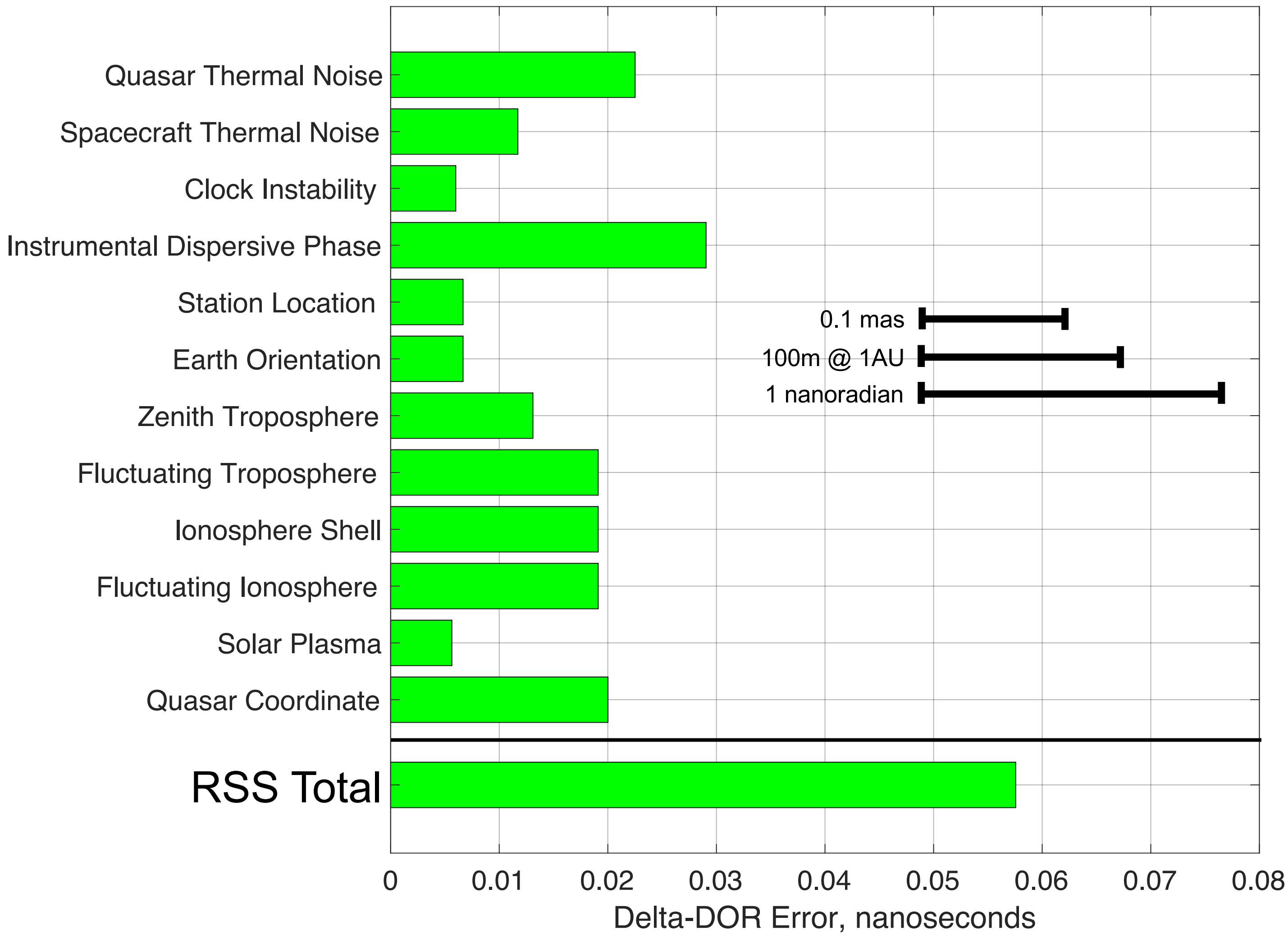
Improved Spacecraft Tech:
- Higher Frequency
- Wider Bandwidths

Improved Ground Tech:
- Higher Recording Rates
- GPS Calibrations
- Improved Ref Frame
- Better Modelling
- Better Scheduling

Motivation for Further Accuracy Improvement

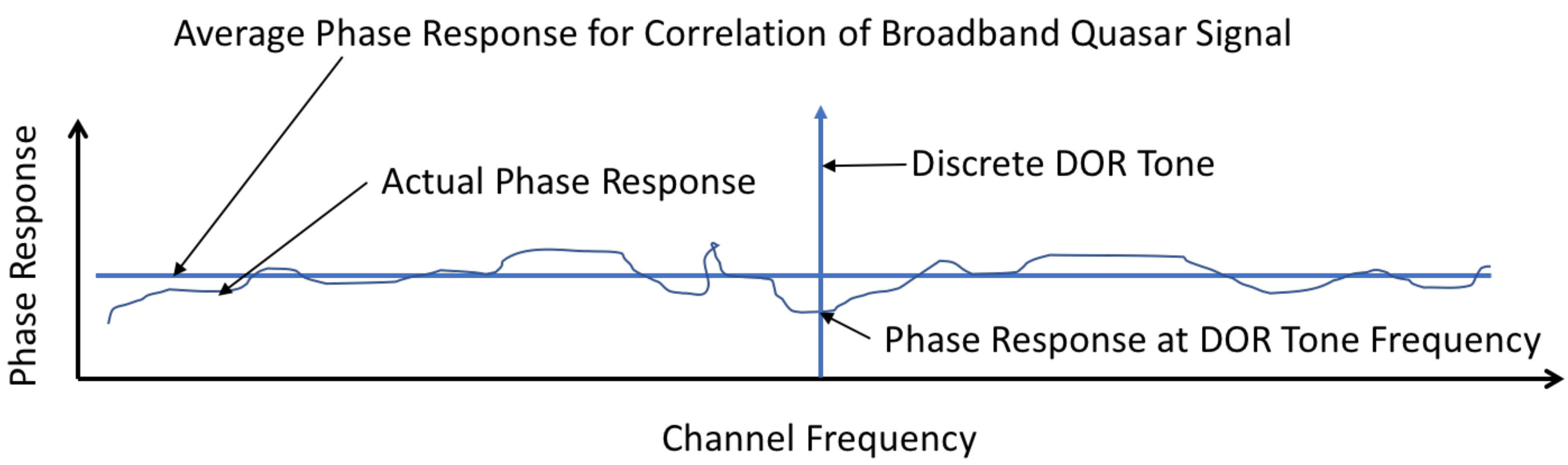
- Improved ΔDOR measurement accuracy provides the following benefits:
  - Would lessen need for long Doppler and range passes
  - Would enable targeting of a more narrow target corridor
  - Can avoid necessity for performing a late maneuver, if a high targeting accuracy is achieved at an earlier time
- Other opportunities for technology improvements:
  - Current 1 MHz DOR tone provides ambiguity resolution of just 1 μs. For missions with lower a priori position knowledge, larger ambiguity resolution is desired.

Baseline ∆DOR Error Budget (X-Band)



Dispersive Phase, The Dominant Error

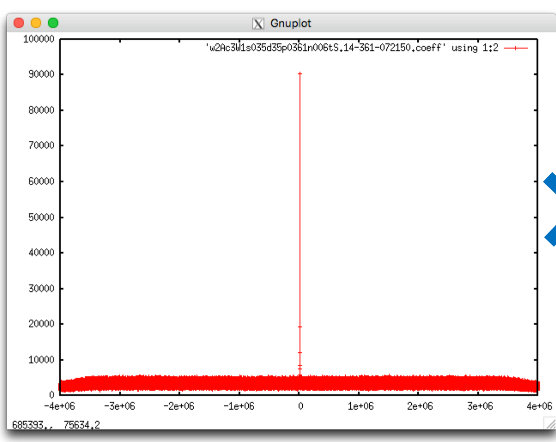
- Dispersive phase is a result of the frequency dependent instrumental phase shift of the recorded signals.
  - Not common to s/c and quasar due to difference in spectrum.
  - Remains as key error source in ΔDOR measurements.



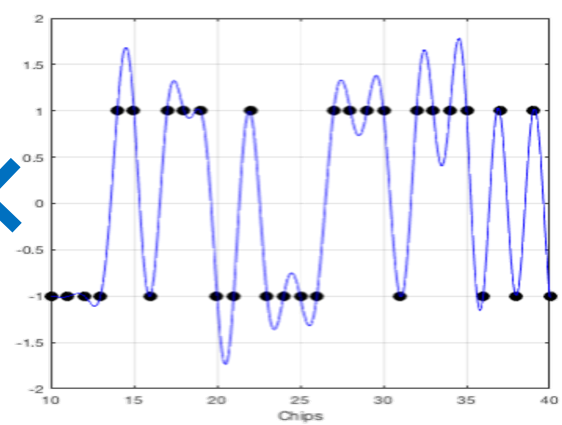
Pseudo-Noise (PN) DOR Signal

- The S/C DOR tone can be spread by a PN sequence.
  - The resulting spectrum is spread by chip rate of the PN code, and further flattened by use of a pulse shaping filter.
  - Estimated cancellation of ~90% of the dispersion error.
  - A long sequence (~1 ms) can be used for ambiguity resolution.
  - CDMA techniques can measure multiple s/c simultaneously.

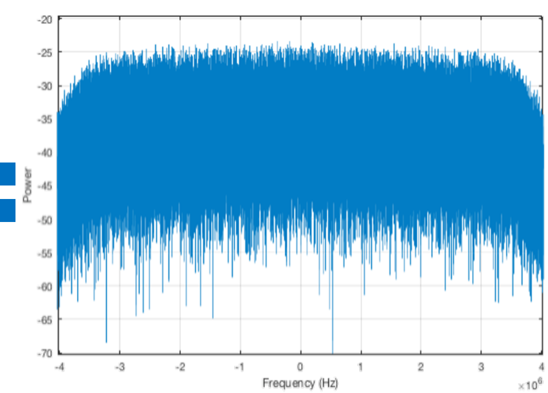
Sinusoidal DOR Signal



8 Mcps PN Sequence



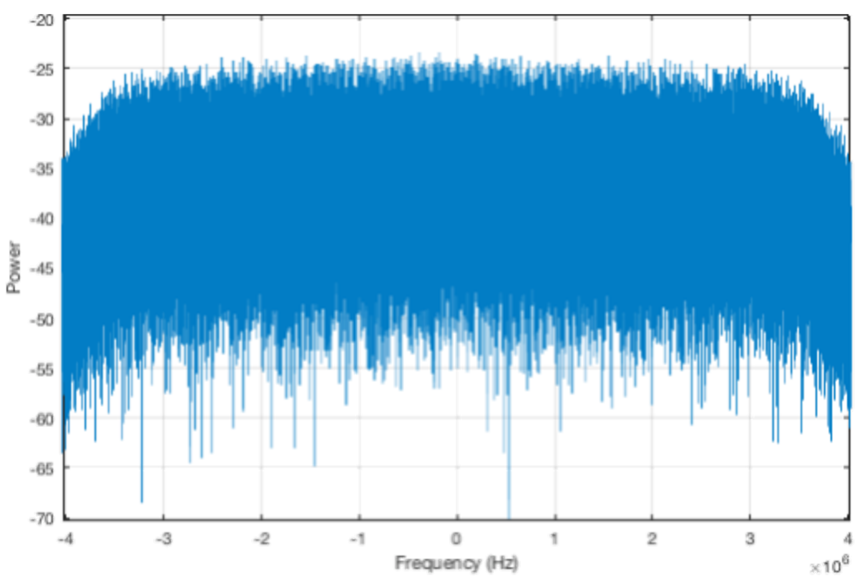
8 MHz PN-DOR Signal



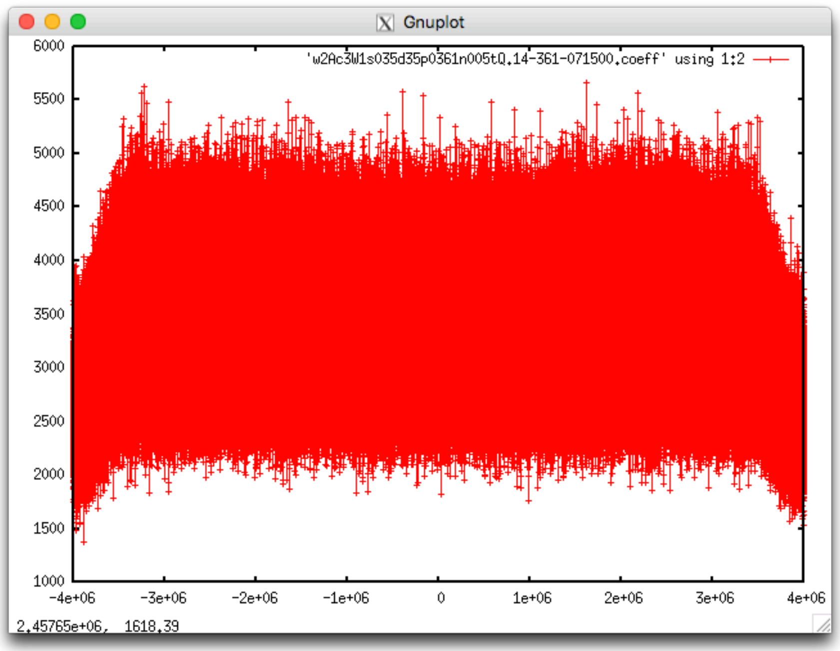
Pseudo-Noise (PN) DOR Signal

- JPL's IRIS CubeSat radio is capable of transmitting spread spectrum PN code DOR signals.
- Recorded spectrum closely matches quasar spectrum.

8 MHz PN-DOR



8 MHz Quasar



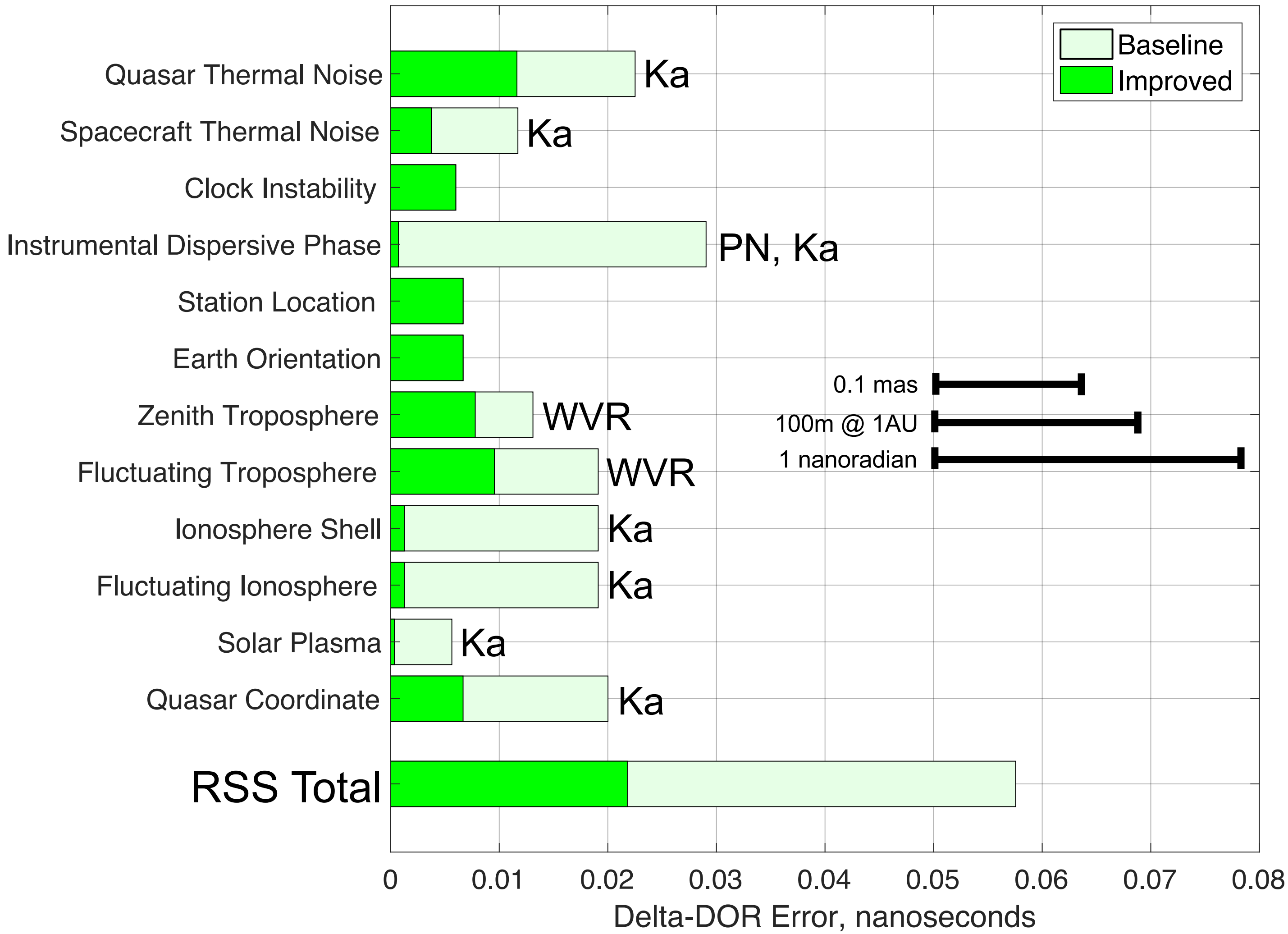
Ka-Band ΔDOR

- Remaining error sources can be reduced by going to a higher frequency signal, Ka-Band (32 GHz)
- Advantages of Ka-Band
  - 4x Wider spanned bandwidth from wider spectrum allocation
  - 4x Higher sampling rates due to increased DOR tone spacing
  - 3x Less quasar coordinate error since quasars generally have smaller cores and less structure. (work in progress)
  - 15x Less charged particle errors at higher frequency (due to $1/f^2$ dependence)
    - Ionospheric effects and solar plasma effects are greatly reduced
- Disadvantages of Ka-Band
  - 2.5x Less flux from Quasars
  - 2x Increased antenna system temperature

Better Troposphere Calibration

- JPL is developing the In-line Water Vapor Radiometer (WVR) which measures water vapor along the same radio antenna path as the spacecraft signal.
  - Driver is improved Doppler data, but will benefit ΔDOR also.
  - Better beam matching increases performance over short time scales necessary for ΔDOR (30-100 seconds).
  - Increased sensitivity over previous designs
- Expected reduction in troposphere errors by a factor of 2.

Improved ΔDOR Error Budget (PN, Ka, WVR)



Summary

- Limiting terms within current ΔDOR error budget include: thermal noise, dispersive phase, ionosphere effects, troposphere effects, and coordinate uncertainty.
- Current technology development efforts aim to reduce leading error sources over next few years.
  - Ka-band (operational): 2x less source thermal noise,15x less ionosphere error, 3x less quasar coordinate uncertainty
  - PN DOR (operational late 2019): 10x less dispersive phase
  - In-line WVR (prototype late 2020): 2x less troposphere error
- Improves ΔDOR error budget from 2 to 0.75 nrad
  - Improves targeting accuracy for Mars landing and other missions.

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